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Analysis of passive feedwater injection in the case of WWER-440/V213 plant blackout

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1. Introduction

Initiating event with complete loss of AC power, called plant blackout, belongs to the typical BDBA accidents for which the time of plant survivability without fuel damage depends solely on built-in safety. Plant blackout results in reactor trip, loss of FW and trip of all RCPs. After RCPs coast down the decay heat is removed from the core in natural circulation mode. On the secondary side the heat is removed via steam dumps to atmosphere what causes continuous reduction of secondary side water inventory. When the secondary side heat sink is depleted, core decay heat results in increasing of primary coolant temperature and pressure. As soon as opening setpoint of PRZ relief valve is reached, primary coolant starts to flow to PRZ bubbler tank and, later, after break of membrane, into confinement. It is obvious that early recovery of electricity supply is necessary condition to prevent serious core damage. Therefore, the time margin to core damage is the matter of importance. Due to relatively low core power and large water inventory on both, primary and secondary sides, WWER-440 units represent robust system and comparing to typical western PWRs, time margin available for recovery of electricity supply is much longer. Furthermore, due to design features of FW system there is, in principle, possibility of passive FW injection into SGs after their depleting. The first phase of the accident is characterised by continuous water depletion from the secondary side of SGs. Here, the results of the analysis of the later phase with passive FW injection into SGs are presented.

2. Basic principles of passive FW injection

The basic idea of passive secondary side "bleed & feed" procedure consists in using water inventory from two FW storage tanks for feeding SGs. The total volume of FW tanks is 2 x 150 m^3, what is more than sufficient for complete refilling of all six SGs. Necessary condition for the successful application of this procedure is depressurisation of SGs below the pressure in FW tank. During nominal operation the pressure in FW tank is 0.7 MPa and the water is saturated. These initial parameters may decrease during the first phase of the accident (depletion of SG inventory) due to heat losses and steam leakage from the upper part of the tank. Nevertheless, due to location of FW tank below the roof of machine room there is still available hydrostatic pressure in addition to internal pressure of FW tank (difference between horizontal axis of FW tank and SG vessel is 12.7 m). Simplified arrangement of the SG feedwater and steam systems is illustrated on Fig.1. Taking into account that both, FW and steam systems are designed for significant mass-flow-rates, limiting factor of the successful application of the passive FW injection into SGs may be limited capacity of the two steam dumps stations into atmosphere, which are available for depressurisation of the secondary side.

3. Analytical support

There were performed several analyses to study the possibility of passive FW injection into SGs. Main goal was to solve the following topics:

- Feasibility of the passive injection; is the capacity of BRU-As sufficient for depressurisation of SGs below the set point for FW injection? If yes, is the capacity of passive FW injection sufficient for long-term cooling?
- In the case of uncontrolled FW injection, is there a danger of overcooling transient, which may result in core recriticality?

Providing that answers of two above mentioned questions are positive, an optimal procedure for long-term core cooling should be found. It should fulfil the following requirements:

- FW delivery sufficient for removing decay heat (controlled maximum primary temperature in order to preserve leaktightness of the RCPs sealing);
- controlled minimum primary temperature or controlled boron concentration (via PRZ relief valve and accumulator injection) in order to control core criticality;
- maximum time margin to core damage;
- reasonable pressure and temperature differences between primary and secondary side of the SGs (integrity of SG tubes);
- minimum requirements on necessary I&C information;
- minimum requirements on operator actions.

The aim of last two requirements is to minimise consumption of DC sources. This topic is not treated in presented paper.

All calculations were performed using RELAP5-3D code. Six loops nodalization scheme was used in the analysis. Characteristic feature of the plant blackout is continuous decreasing of the SG water level during the accident. Limitation of the western system transient analysis codes for description of horizontal SGs under the conditions with secondary side water level changes were discussed in [1], [2]. Therefore special nodalization scheme with increased number of rows representing SG tubes was developed and presented in [1] in order to model properly smooth reduction of flooded heat transfer area between primary and secondary during the accident (Fig. 2). Main attention was paid especially to nodalization of the middle and lover part of SG tube bundle.

In the nodalization scheme of the FW storage tank and FW pipes, attention was paid to modelling of basic geometrical (lengths, diameters, elevations) as well as hydraulic characteristics (resistance of bends, protective riddles, FW pumps and armatures). Differences between the lengths of FW pipes between FW header and individual SGs were taken into account. Taking into account importance of heat losses during long-term transients, heat structures were modelled in FW pipes and FW storage tanks.

At the beginning, nominal operation of the reactor was assumed. Plant blackout was assumed at time t = 0 s. After reactor trip, conservative core decay heat corresponding to the end of fuel cycle was used in analysis (ANS-79-1). In all calculations it was assumed that the leaktightness of the RCPs seals is preserved during the accident. First operator interventions were assumed 10 minutes after initiating event. Heat losses have been modelled on both, primary and secondary side.

4. Results

The first results have confirmed the feasibility of passive FW injection into SGs. It was shown that the full opening of both BRU-As even results in uncontrolled FW injection followed by partial overfilling of SG and overcooling transient. Minimum coolant temperature in primary system drops significantly below the recriticality threshold. Control of the FW injection or boration of primary system is therefore necessary. Here, the results of controlled FW injection are briefly presented (Figs. 3.1-3.8).

The presented procedure with controlled FW injection can be split into two phases. In the first phase of the accident, 10 minutes after beginning of the accident, there is initiated the cooling down of the primary system with chosen trend 30 °C/hour using BRU-As. During this initial phase the secondary pressure and SG water level are dropping monotonously and the BRU-As are still more and more open in order to keep the prescribed trend. The goal of the first phase is to depressurise the secondary side of SGs to the level of pressure in FW tank. Cooling down of the primary system with prescribed trend is therefore continuing till the passive FW injection is initiated. During the depressurisation phase of the secondary side, some FW trapped in high-pressure part of FW system (between SGs and check valves on FW pumps discharge) enters into steam generators.

In the second phase of the accident, the procedure based on controlled constant primary temperature ~ 230 °C in cold legs is applied. Primary temperature is again maintained by BRU-As opening. This way controlled FW injection is reached. Passive injection is initiated about 2 hours after the beginning of the accident, when the pressure in SGs drops to ~ 0.63 MPa and water level in SGs is ~ 0.8-0.9 meters. At this time the primary parameters are as follows: reactor inlet temperature ~ 208 °C, outlet temperature ~222 °C, pressure ~9.3 MPa. Pressurizer is almost empty. Concrete values of the primary and secondary parameters are influenced by selection of initial and boundary conditions (for example decay heat, initial SG levels, etc.). Due to differences in hydraulic characteristics of FW lines there are significant differences also in the distribution of FW injected into SGs. After first FW injection the steam removal through BRU-As is reduced in order to reach primary temperature ~ 230 °C in cold legs. Consequently, water level in PRZ rises again. Further control of primary temperature is ensured by cyclic opening and closing BRU-As (1^{st} BRU-A is permanently partially open, periodical full opening of both BRU-As), caused by considered simplified BRU-A control model in the calculation, what results in oscillating behaviour of the primary temperature and PRZ level. The FW is injected into SG during the periodical opening of BRU-As. These discrete injection pulses result in stepwise decreasing of water inventory in FW tanks and oscillating behavior of water level in SGs. Despite of stabilised reactor inlet/outlet temperatures, the primary pressure is slowly decreasing due to heat losses from PRZ and upper part of the reactor vessel (stagnation volumes). About 14 hours after initiating event the primary pressure drops below 6 MPa, what is the design value of accumulator pressure in WWER-440/V213 units. However, in the case analysed the 4 MPa accumulator pressure was considered (due to intended decreasing of the accumulator pressure at some VVER-440/V213 NPPs), therefore the accumulator injection is not initiated. Calculation was terminated about 20 hours after initiating event when both FW tanks were completely depleted. The water level in SGs was at this time ~ 0.3 - 0.5 meters.

5. Conclusions

The results of performed analysis demonstrate feasibility of passive FW injection from two FW storage tanks into SGs in the case of plant blackout. This may increase significantly time margin available for recovery of electricity supply without core damage. From the analyses performed it follows that initial SG secondary side inventory as well as water in FW tank are sufficient for more than 20 hours of reliable core cooling. Full opening of both BRU-As may result in overcooling transient and core recriticality. Controlled FW injection is therefore necessary. Different ways for controlling criticality can by applied: either to keep higher primary temperature or to depressurise primary system (via PRZ relief or safety valves) below accumulator pressure and to add the boron into primary.

Abbreviations

AC	alternate current
BDBA	beyond design basis accident
BRU-A	steam dump to the atmosphere
DC	direct current
FAV	fast acting valve
FW	feed water
HPH	high pressure heater
LOCA	loss of coolant accident
MSH	main steam header
NPP	nuclear power plant
PRZ	pressurizer
PWR	pressurized water reactor
RCP	reactor coolant pump
RV	relief valve
SG	steam generator

References

[1] P. Matejovič, Ľ. Vranka, M. Bachratý: Analysis of plant blackout of WWER-440/V213 NPPs, 4th International Information Exchange Forum on Safety Analysis for NPPs of WWER and RBMK types, Obninsk, RF, 11-15 October, 1999

[2] P. Matejovič, Ľ. Vranka, E. Václav: Application of the thermal-hydraulic codes in VVER-440 steam generators modelling, Third International Seminar on Horizontal Steam Generators, Lappeenranta, Finland, 1995

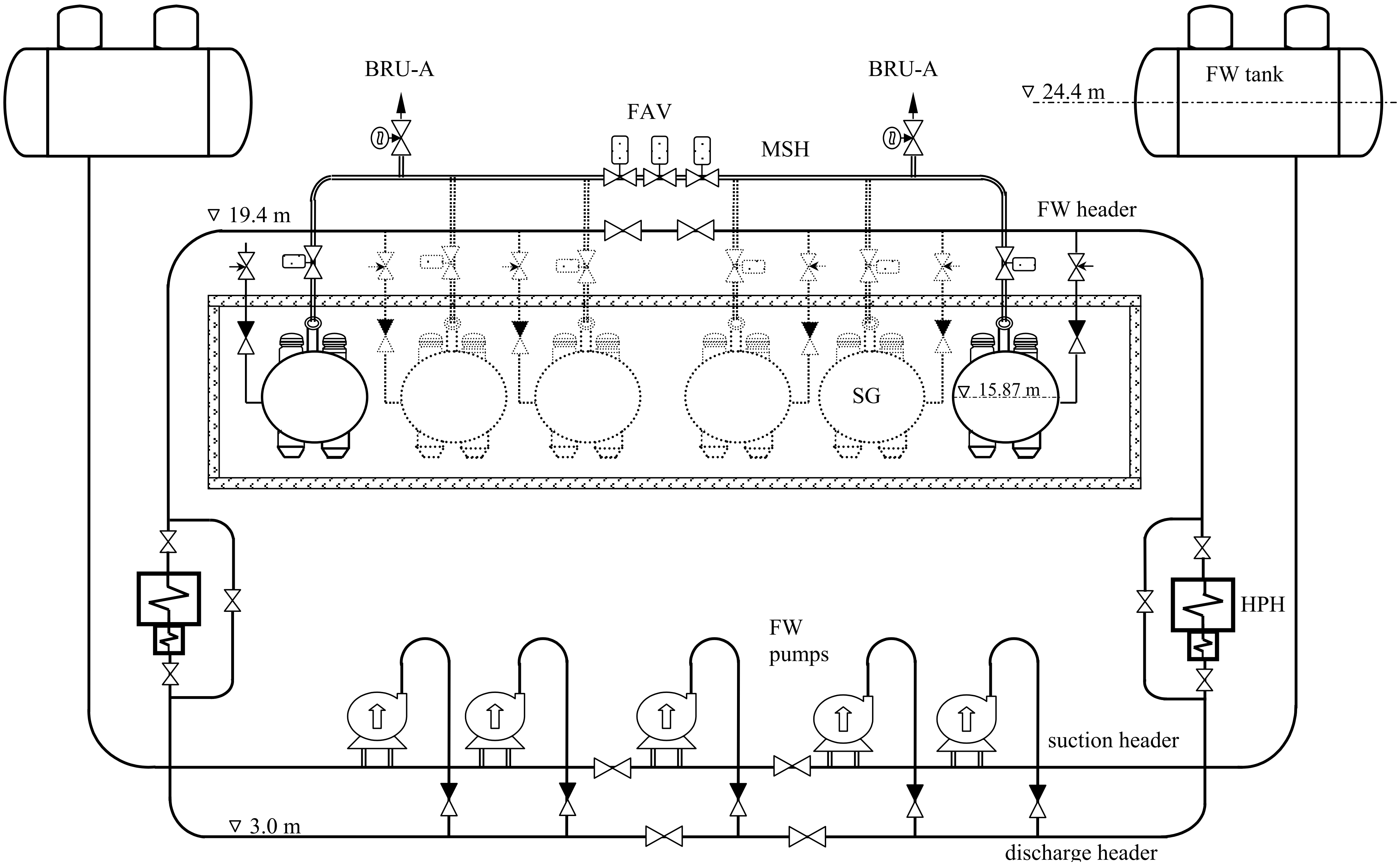

Fig. 1. Illustration of the FW and steam systems

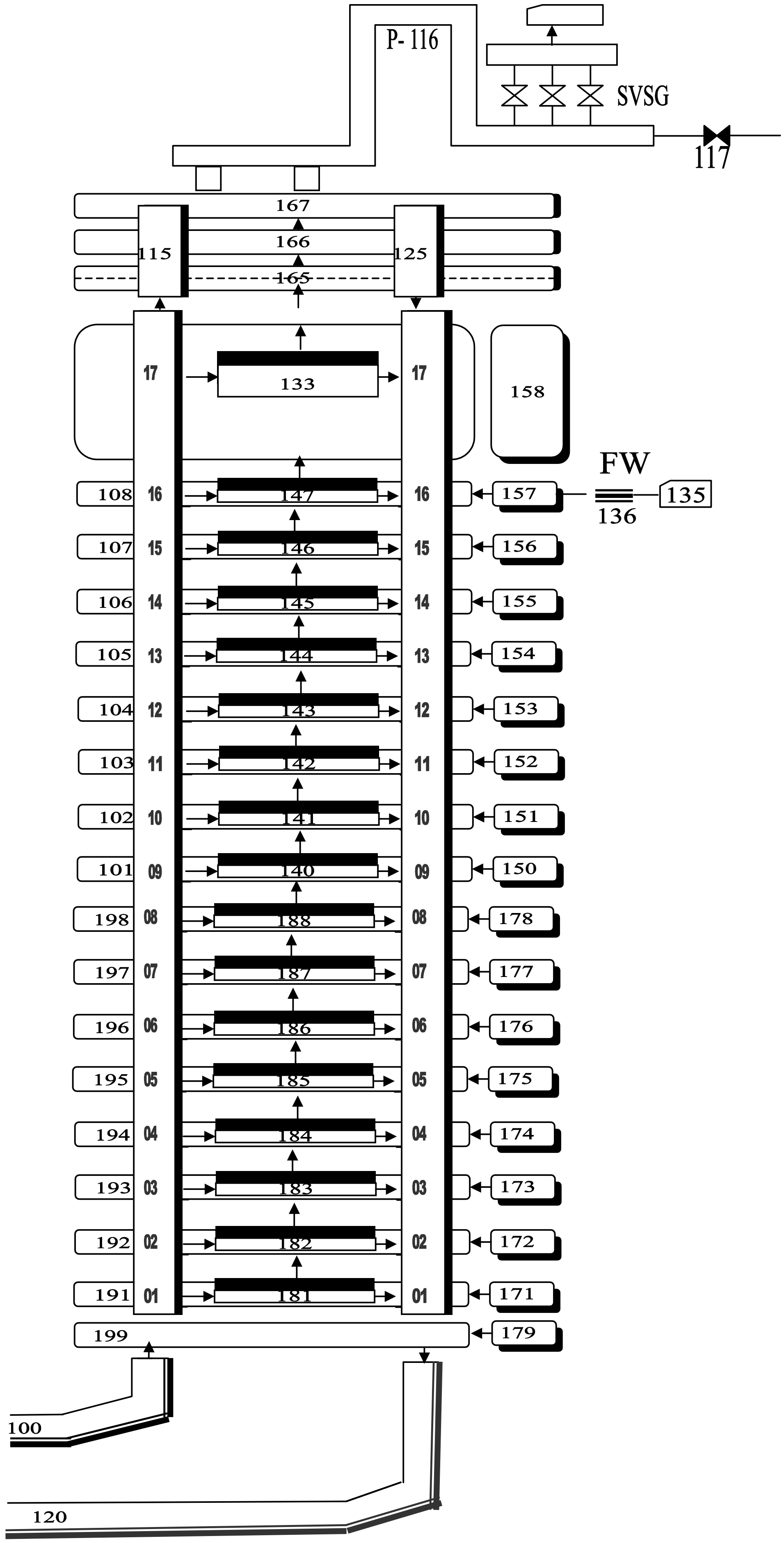

Fig. 2. Refined nodalization scheme of SG for station blackout analysis

Fig. 3.1. Pressure in primary system, MSH and FW tank.

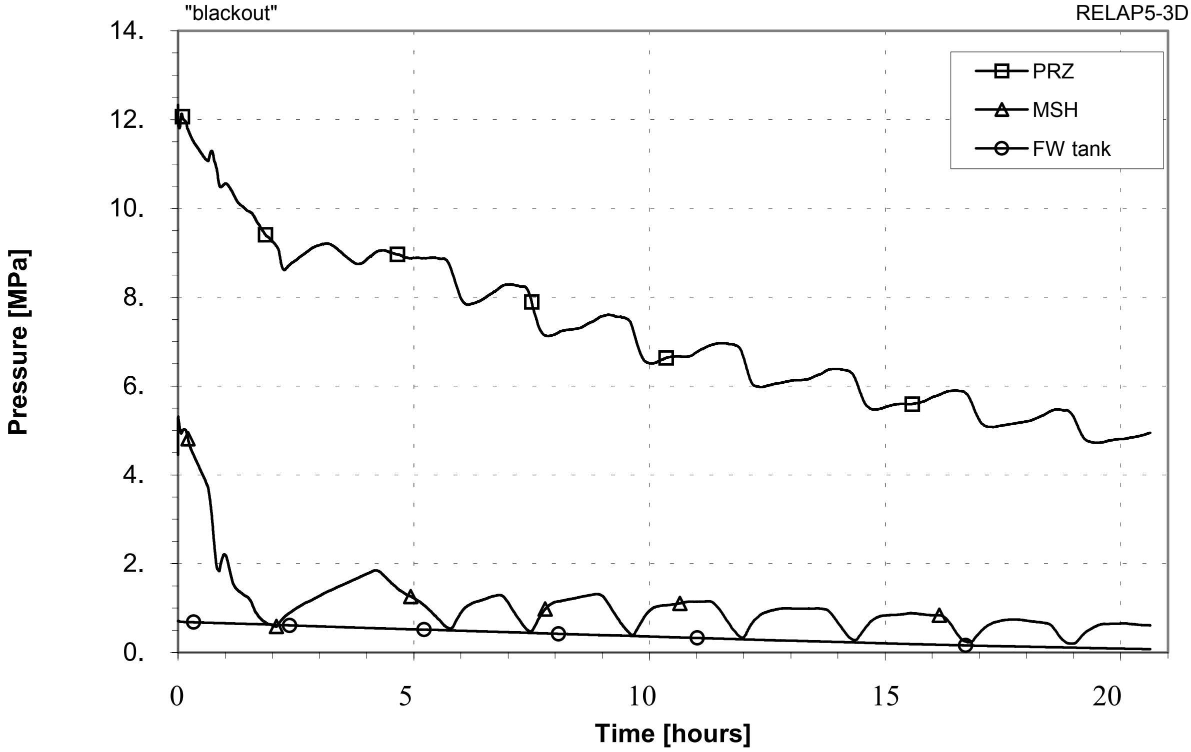

Fig. 3.2. Coolant temperatures in reactor vessel.

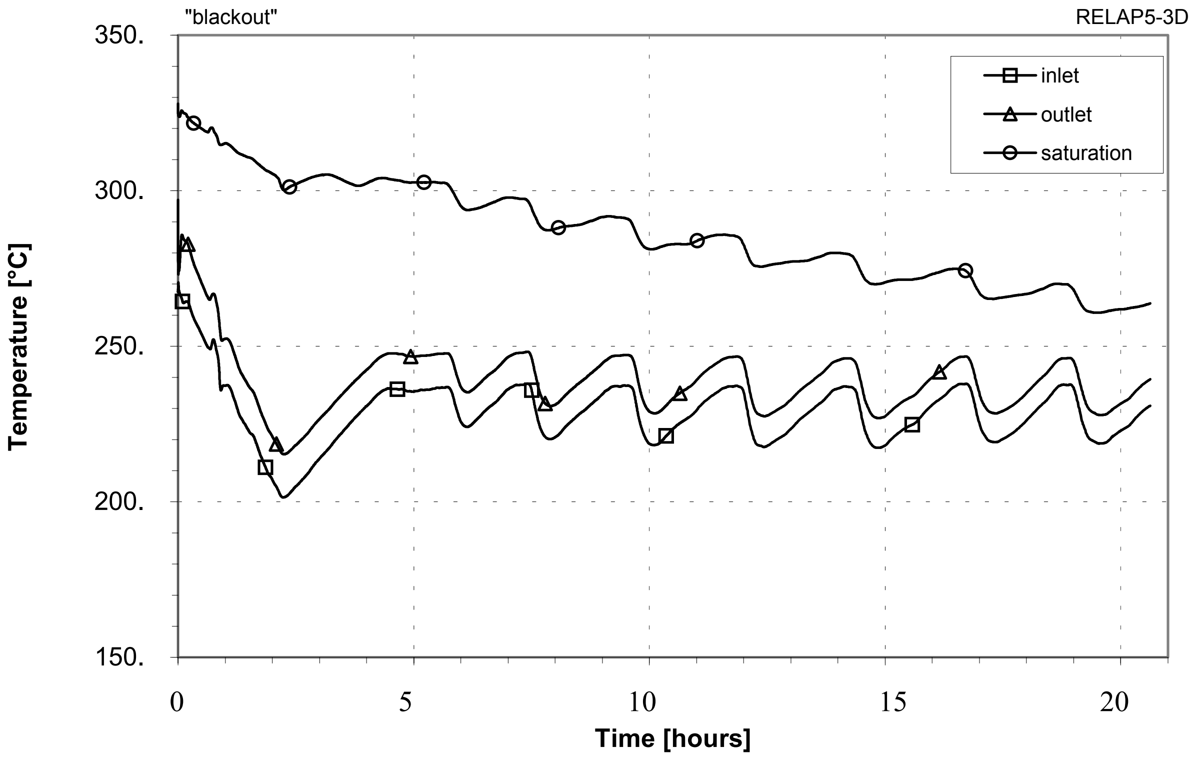

Fig. 3.3. Collapsed water level in SGs.

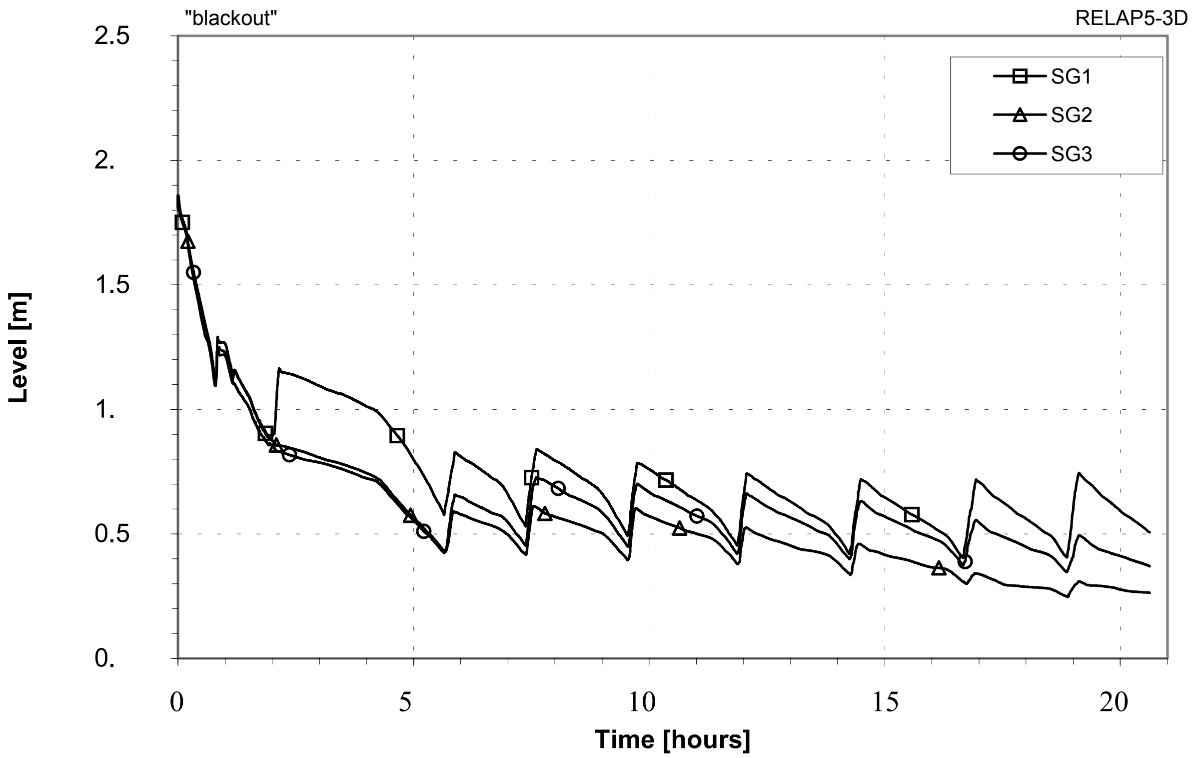

Fig. 3.4. Collapsed water level in SGs.

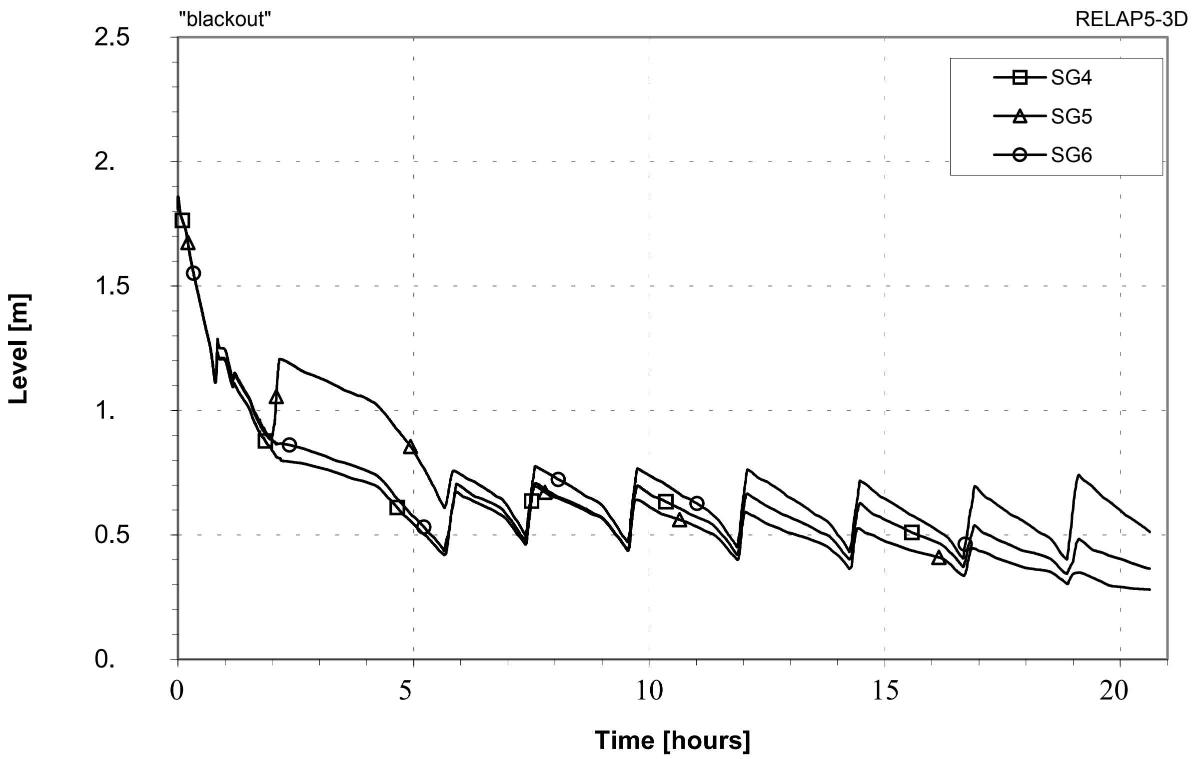

Fig. 3.5. Collapsed water levels in PRZ, reactor and FW tank.

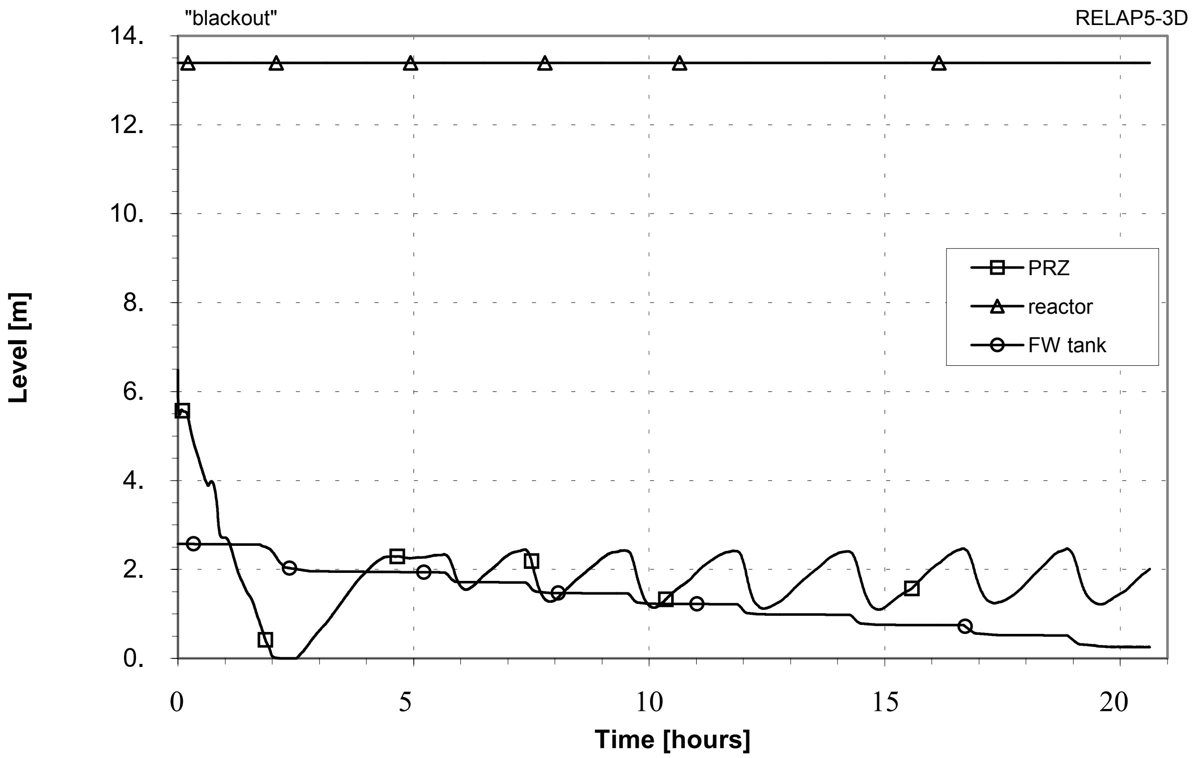

Fig. 3.6. FW mass-flow-rate into SGs.

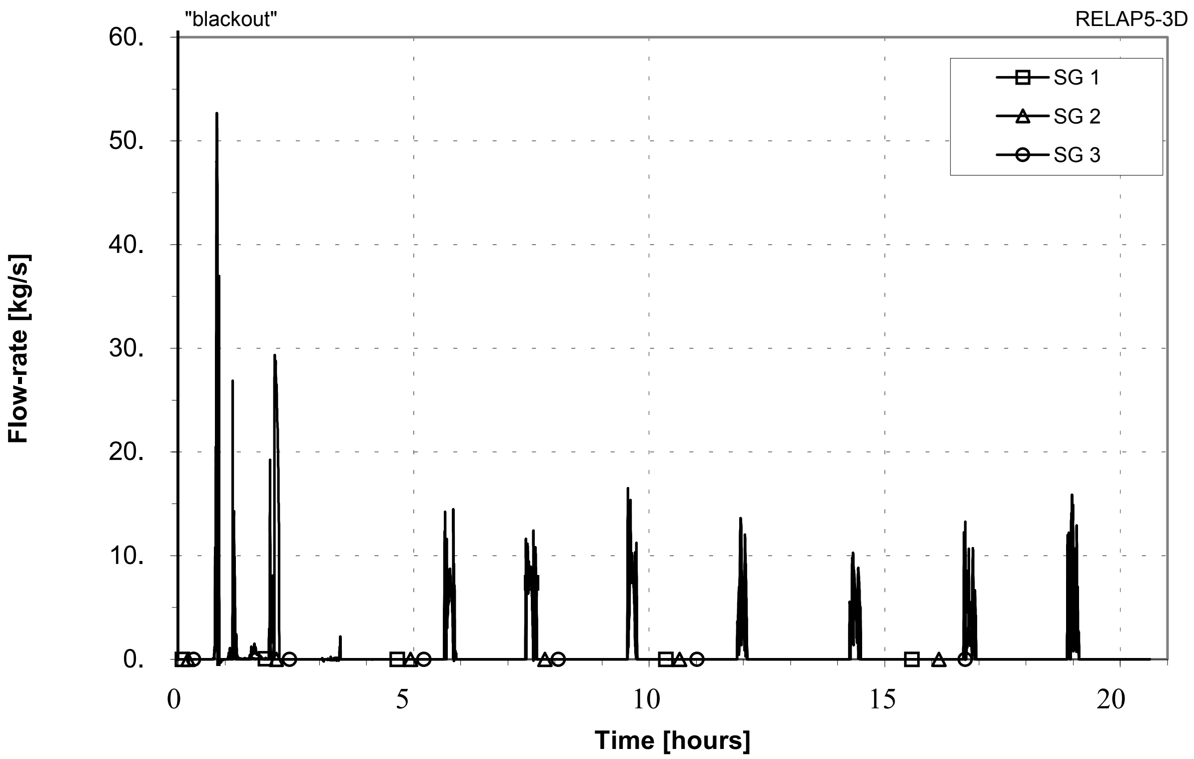

Fig. 3.7. Mass-flow-rate through BRU-As.

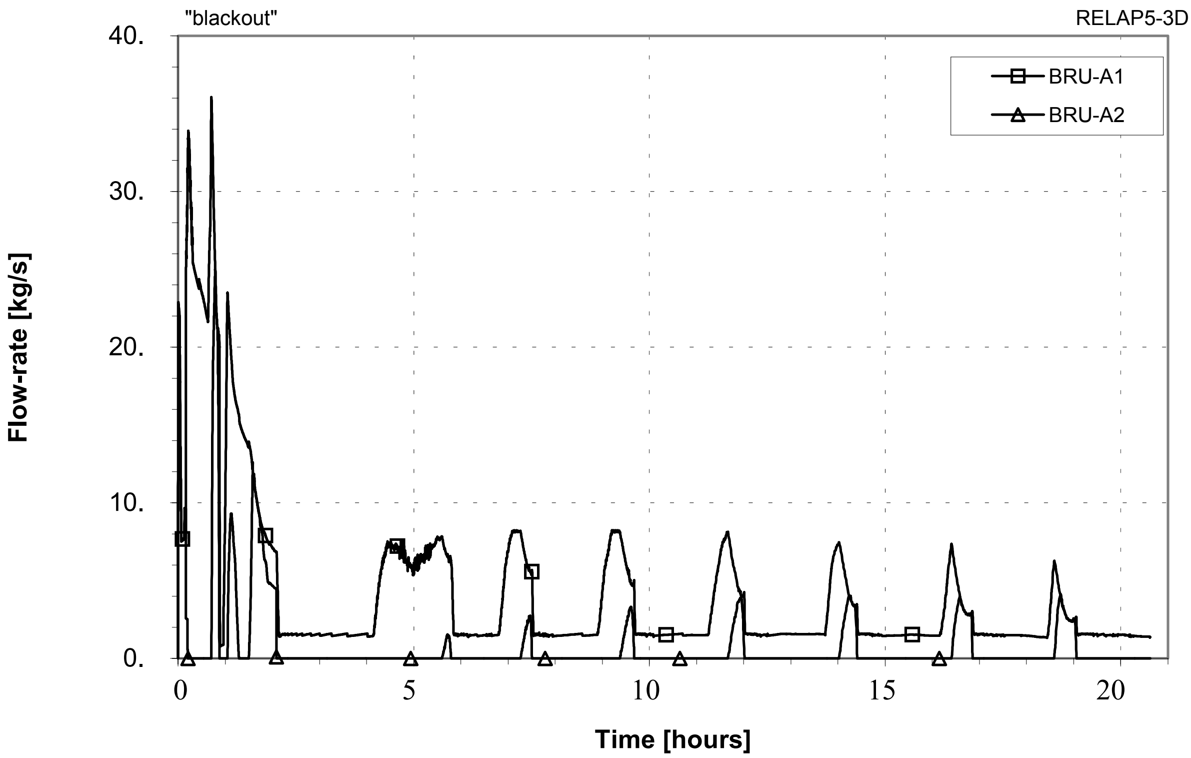

Fig. 3.8. Opening of BRU-As.